ON HEAT TRANSFER IN NUCLEATE BOILING-(2)

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ABSTRACT. Attempts have been made to measure the maximum heat flux attainable in the nucleate boiling range for di-ethyl ether boiling on horizontal platinum wires and copper tubes. The flux shows a dependence on the diameter of the heating surface. With smaller diameters of the wire the maximum heat flux increases. A full Nukiyama curve was also tried to be obtained. Though only the nucleate boiling range, and the film boiling cum radiation zone were experimentally traced, the transition range from nucleate boiling to steady film boiling was also possible to be constructed with considerable definiteness. From the data a value for the Liedenfrost point for the liquid has also been suggested. The heat transfer coefficient at any given heat flux has been found to increase with the diameter of the heater wire decreasing. Moreover, the hysteresis effect has been found also to decrease with the diameter of the heater wire decreasing.

INTRODUCTION

The present day heat exchangers are being operated at higher and higher heat fluxes. The nucleate boiling phenomenon is very interesting in such a case because it offers very high rates of heat transmission. As the temperature difference between the heater surface and the bulk liquid increases, the rate of heat transmission gradually increases till it reaches a point when suddenly the heat transfer coefficient drops to very small value. Lang (1888) was the first to report this sudden drop in the rate of heat transmission. He reported on a sea water evaporator operated under pressure and heated by high pressure steam. His experiment clearly indicates that the overall coefficient attains a maximum when the temperature difference lies between 40 and 50°C and also shows a decrease in rate of boiling as ΔT is increased beyond this value. The experiment of Pridgeon and Badger (1924) on sea-water evaporators definitely show decreasing coefficients at temperature differences in excess of 25°C. Numerous experimenters have reported also that overall coefficients increase with ΔT less and less rapidly as higher value of the coefficient are reached.

Jacob and Linke (1933) obtained in the case of water a maximum heat transfer coefficient at a temperature difference of 15.5°C. Any attempt to reach a higher temperature difference caused the heater to burn out. However, no report of the maximum heat transfer coefficient was available from their experiments with Carbon terachloride.

Mosciki and Broder (1926) experimented with a wire heater. They found that when the wire had attained a certain temperature excess over the surrounding liquid, a slight increase in power input caused a sudden rise in wire temperature and melted the wire. Nukiyama (1934) took up the steps followed by Mosciki and Broder and he seemed to be the first man who realized that maximum rate of boiling might occur at a moderate temperature difference. He boiled water at atmospheric pressure with electrically heated nichrome, nickel and platinum wires of various diameters (0.14-0.757 mm) and, by measuring the electrical resistance of the wire, determined its temperature for the various heat loads. However using a platinum wire of 0.014 mm. in diameter Nukiyama, was able to obtain a boiling curve which is reproduced in modified form in fig. 1. As the heat load increases the left hand branch of the curve is followed. At the point A, a slight increase in heat input causes a sharp rise in wire temperature and the

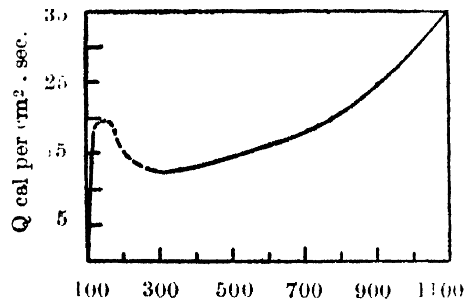


Fig. 1. Boiling curve of Nukiyama.

operating point jumps to B. If the heat load is increased still further the point B shifts to point D. But if the heat load is gradually decreased the right hand curve is followed upto C and then again a temperature jump occurs and the working point shifts to the left hand branch of the curve. Nukiyama stated that the dotted portion of the curve represents an unstable region, but his work clearly shows the existence of a maximum rate of boiling at a critical temperature difference of 40-50°C for water.

This method of experiment has the disadvantage that at higher temperatures the wire sags and the true heat transfer area becomes suspect as was rightly pointed out by the students of Prof. W. H. McAdams to Drew and Mueller (1937).

The experiments carried out on the line of Nukiyama also offer in addition to the determination of the maximum rate of heat transfer the minimum temperature of a steady spheroidal state for the liquid.

Mosciki and Broder found the limiting temperature of the wire to be independent of the main body temperature of the liquid. This seems to indicate that the limiting factor is primarily the temperature at the heating surface-liquid interface. Upto the breaking point the liquid adjacent to the wire, would, in all cases, be at the temperature of the latter, and the only essential change in local conditions caused by lowering of the bulk temperature would be a steepening of the temperature gradient in the liquid.

Though much has been said about the nature and orientation of the surface on the overall coefficient of it has been shown by Berenson (1962) that the maximum nucleate boiling heat flux is independent of the surface conditions.

The present set of experiments were undertaken to find data in the case of di-ethyl ether boiling on horizontal wires and tubes for investigation of the maximum heat flux, the critical temperature difference and the Liedenfrost point.

Experiments were performed with platinum wire heaters of 004 cm, .005 cm and 0.1 cm. diameter and thin walled (0.004″) 3/16-th inch diameter copper tubes.

Experimental apparatus

Heater : The construction of the tube heater (copper tube) was described earlier (Basu, 1964). The heater cell using platinum wire as the heater was made on the same lines as by Ahsmann and Kronig (1951). It consists of a fine thermopure platinum wire placed along the axis of a horizontal cylinder made of brass The end plugs are made of perspex. The detailed construction of the heater cell is shown in the fig. 2. At one end, the wire is screwed to a brass plug, fitting

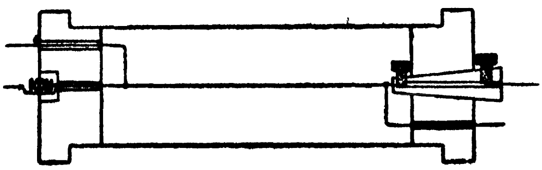


Fig. 2. Constructional details of the heater.

closely into the plug and passing centrally through it. The other end of the wire passes through the centre of the end plug and is soldered to a spring. This was done with a view to prevent sagging of the wire. One of the current leads is screwed to the outside end of the brass plug and the other is soldered to the spring. The potential leads were soldered to the platinum wire and taken out through holes drilled in the plugs. The internal diameter of the brass cylinder was 2.1 cm. and rows of 1/8″ holes were drilled all other the body so as to ensure the free circulation of the liquid.

The details of purification of the liquid was described earlier (Basu 1964).

RELATION BETWEEN THE SURFACE TEMPERATURE OF THE HEATER WIRE AND ITS AVERAGE VOLUME TEMPERATURE.

The temperature of the wire was measured by resistance thermometry. The heating current was allowed to flow through a series circuit containing the heater cell and a standard 0.1 ohm resistance. Then by comparing the potential differences across the standard resistance and the heater length between the potential leads the resistance of the heater (platinum) was determined at each heat load. Then from the temperature coefficient of platinum the temperature of the wire was determined. The potential differences were measured by a Diesselhorst thermoelectric-free potentiometer capable of measuring down to 0.1 micro volt. The actual measurements were taken down to 1 micro volt only. The bulk temperature was measured by three welded type single junction thermocouples (Copper-constantan).

The temperature measured in this way is the average volume temperature of the wire. In our calculation we have assumed this temperature to be equal to the surface temperature following the lines of Sato *et al* (1962) who have also shown that for very thin wires, as in our case, the average volume temperature is only slightly higher than the surface temperature.

In the boiling range the temperature change (ΔT) of the heater wire is small. For unit length of the platinum wire heat balance is given by ,

$$-2\pi k \frac{dT}{dr}\, dr - 2\pi kr \frac{d^2T}{dr^2}\, dr = 2\pi Qr\, dr \qquad \dots \quad (1)$$

where T = temp. of the platinum wire at radius r,

K = Thermal conductivity of the platinum wire and

Q = Heat produced per unit time per unit volume.

Boundary conditions here are,

$$\left(\frac{dT}{dr}\right) = 0 \quad \text{at} \quad r = 0$$

$$-K\left(\frac{dT}{dr}\right)_{r=r_1} = h(T_S - T_B), \text{ at } r = r_1 \text{ (surface)}$$

where, h = heat transfer coefficient at surface,

T_S = Surface temp. of the wire and

T_B = Bulk temp. of the liquid.

Under these boundary conditions, equation (1) reduces to

$$T = \frac{Q}{4K}(r_1^2 - r^2) + \frac{Qr_1}{2h} + T_B \qquad \dots \quad (2)$$

where r_1 is the radius of the wire.

On the other hand, the average volume temperature is given by,

$$T_V = \frac{1}{\pi r_1^2}\int_0^1 2\pi T r\, dr = \frac{Qr_1^2}{8K} + \frac{Qr_1}{2h} + T_B \qquad \dots \quad (3)$$

Putting in equation (2) $T = T_S$ for $r = r_1$

$$T_S = \frac{Qr_1}{2h} + T_B$$

Therefore,

$$T_V - T_S = \frac{Qr_1^2}{8K} \qquad \dots \quad (4)$$

Now Q, the heat produced per unit time per unit volume, and q, the heat flux are related as

$$Q = \frac{2q}{r_1},$$

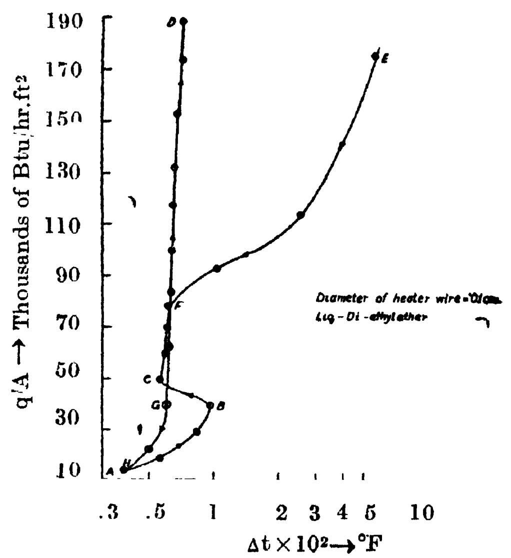
So, equation (4) becomes,

$$T_V - T_S = \frac{r_1}{4K} \cdot q \qquad \dots \quad (5)$$

Equation (5) enables one to calculate the surface temperature. From the above equation it is also evident that the departure of the surface temperature from the average volume temperature is a maximum when the heat flux q is a maximum.

RESULTS

Experiments were performed with wires of platinum of diameter 0.004 cm 0.005 cm,. 01 cm. and thin walled copper tubes (wall thickness .004″) having a diameter of 3/16th inch.



Fig· 3. q/A Vs Δt curves.

In the present set of experiments the values of critical heat flux, the critical ΔT and the maximum heat transfer coefficient are obtained for di-ethyl ether boiling on horizontal platinum wires. Data are also presented for ether boiling on horizontal copper tubes, The value of heat transfer coefficient is only stated in the latter case at a particular value of heat flux.

Fig. 3 shows the boiling curve obtained with platinum wire of diameter .01 cm. In this case the heat flux was increased and the curve ABCD was traced and then the temperature jump occurred and the operating point shifted to E. Decreasing the heat flux the curve EFGH was traced.

Fig. 4 gives the boiling curves for .004, .005 and 01 cm. diameter wires. The maximum heat flux values in these cases were slightly below that at which the temperature jump occurs. The hysteresis effect is present in all the cases. For decreasing values of heat flux the curves become almost straight lines.

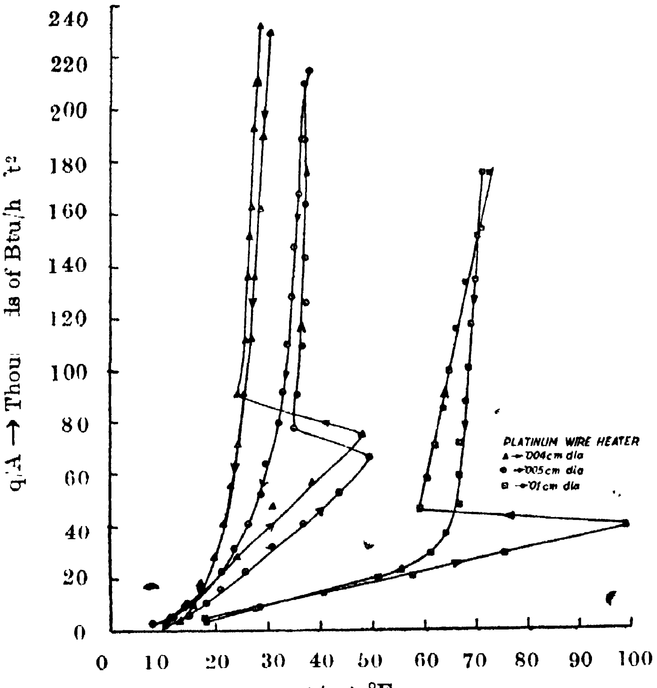


Fig. 4. q/A vs Δt curves.

Fig. 5 show the variation of heat transfer coefficient h, with ΔT for .004, 0.005 cm and .01 cm. platinum heaters respectively.

Fig. 6 shows in the case of 0.004 cm, 0.005 cm, 0.01 cm diameters, the nature of variation of heat flux with T in the radiation zone to the nucleate range across the unstable film boiling region drawn to the same scale.

Table 1 shows the difference between the average volume temperature of the wires, as measured in our experiment, and the surface temperature of the wires.

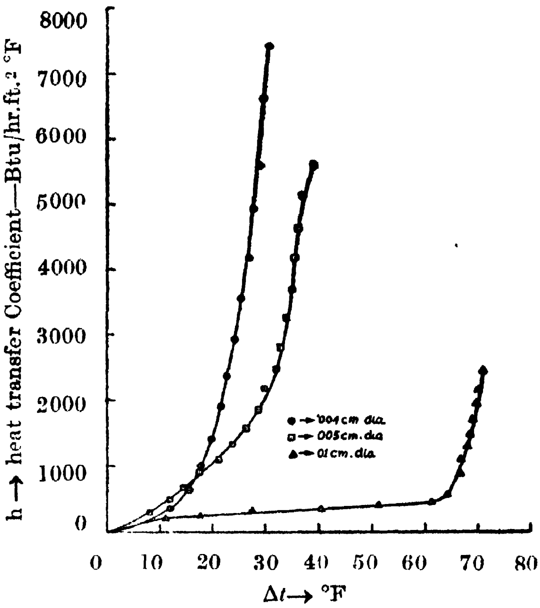


Fig. 5. h vs Δt curves.

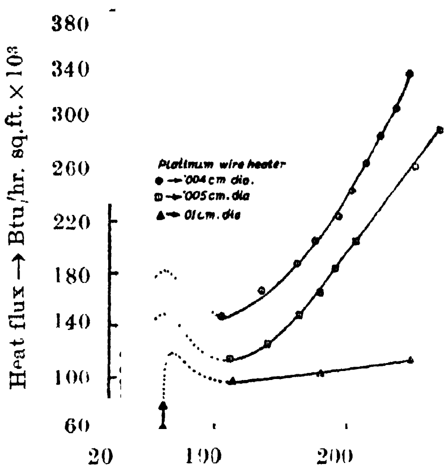


Fig. 6. q/A vs Δt curves.

Table II shows in a condensed form the different results obtained in our experiment.

DISCUSSION

From the present set of experiment it is clear that when heat flux is increased the value of ΔT at which the temperature jump occurs may be different for heater wires of different diameter but after the temperature jump to the right has occurred and stable film boiling has set in, if the heat flux is now decreased step by step gradually, then at a characteristic value of ΔT another temperature jump occurs and the operating point is shifted to left now to a point in the nucleate

TABLE I

Heat flux Btu/hr.ft^1	$(T_v - T_s)$ °F for the heater wires of diameter		
	1.312×10^{-4}ft.	1.64×10^{-4}ft.	3.28×10^{-4}ft.
50×10^3	0.02008	0.0251	0.0502
100×10^3	0.04016	0.0502	0.1004
150×10^3	0.06024	0.0753	0.1506
200×10^3	0.08032	0.1004	0.2008
250×10^3	0.1004	0.1255	0.2510
400×10^3	0.1606	0.2008	0.1016

TABLE II

Diameter of heater ft.	Heat flux Btu/hr. ft^2	ΔT °F	Heat transfer Coeff. (h) Btu/hr. ft^2°F.
1) 1.312×10^{-4} (Platinum)	232.07×10^3	29.36	7904.3
3) 1.64×10^{-1} ,,	215.27×10^3	38.11	5601.5
4) 3.28×10^{-4} ,,	176.26×10^3	72.70	2424.5
4) 1.562×10^{-2} ,,	42.1×10^3	18.9	2230.0

boiling range of the boiling curve. This value of ΔT is, however, found to be almost independent of the diameter of the wire and for ether boiling on horizontal platinum wires assumes almost a constant value of about 110 °F with wire diameters decreasing the boiling curve becomes more and more steep, i.e., the heat transfer coefficient has greater values with thinner wires for the same heat flux. Though in the reverse case when thicker and thicker wires are taken the heat transfer coefficient falls but after a certain value of the diameter, the coefficient appears to become independent of the diameter. The reason may be that with very thin wires the bubble diameter at detachment becomes comparable with the diameter of the wire. The reason is augmented from the experimental finding that as the wire diameter decreases the hysteresis loop also decreases in size, i.e., the wire becomes less and less superheated.

Let us consider the family of boiling curves shown in the Fig. 7. In a cooling operation in the radiation region the initial operating points of the curves in a decreasing order of heater wire diameter are D, D' etc. For curve (1) as the heat flux is decreased, the operating point gradually shifts to C. At this point the temperature jumps and the operating point shifts to B. As the heat flux is decreased further, the curve BA is traced. The portion AB is a region of stable nucleate boiling while CD represents stable film boiling, radiation occurring across the vapour belt. The point C is the point at which stable film boiling begins and it appears from the experimental run, to be characteristic for a particular heater-liquid combination. The nature of the dotted curve BC could not, however,

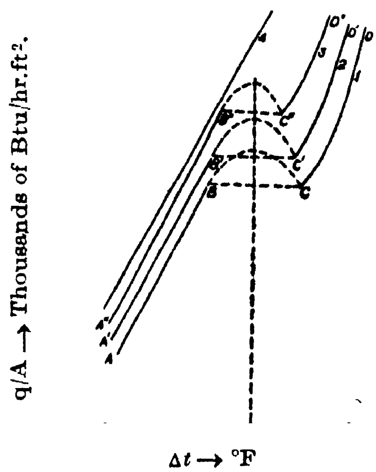


Fig. 7. Theoritical q/A vs Δt curves.

be ascertained from this particular set of experiments. The Liedenforst point should, however, lie somewhere between B and C.

From the nature of the curves it is suggested that when the wire diameter is zero, i.e., in the case of a volume-heated liquid, the unstable region shown dotted in the experimental curves should vanish. Moreover from the given experimental curves what is found is that the range B to C shortens symmetrically as the wire diameter decreases. This, however, enables one to construct the unstable dotted region as a close approximation as shown in the curves. The Liedenforst point which is characteristic of the liquid and independent of the heater wire diameters in all probability, therefore, corresponds to a value of Δt lying between B and C, B' and C', B'' and C'', etc. but is the same point. This in the case of di-ethyl ether is found to be 143°F.

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